Turbulence intensity impact on Windcube accuracy

Workshop on Vector Averaging Versus Scalar Averaging
Vilnius, 2018-05-14

LEOSPHERE

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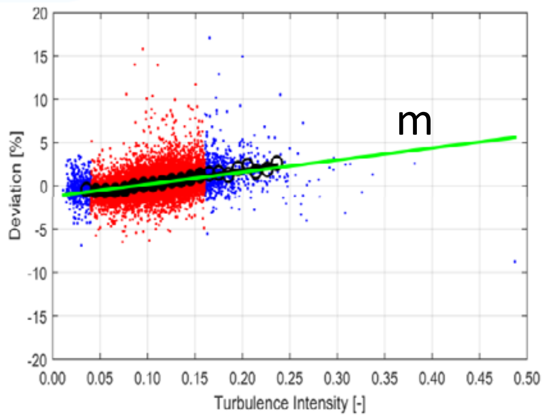
Averaging method of RSD: timeline

- July 2017: different Windcube accuracy observed at two different sites,
- End of 2017: Study on scalar averaging method for RSD -> scalar averaging for RSD is biased in high turbulence wind flow,
- 2018 : Workshop at Vilnius to present outcomes and discuss averaging methods with the Wind Industry.

Repeatable sensitivities to turbulence



Example of sensitivity to turbulence

Height	Variable		m
[m]	name	unit	[% / u.v.]
134.8	Wind Shear	[-]	-3.5
	Turbulence Intensity	[-]	19.3
130.8	Wind Shear	[-]	-2.8
	Turbulence Intensity	[-]	20.7
120.8	Wind Shear	[-]	-2.8
	Turbulence Intensity	[-]	19.3
99.8	Wind Shear	[-]	-1.4
	Turbulence Intensity	[-]	17.9
81.8	Wind Shear	[-]	-1.0
	Turbulence Intensity	[-]	16.3
60.8	Wind Shear	[-]	-1.1
	Turbulence Intensity	[-]	17.9
40.8	Wind Shear	[-]	-4.2
	Turbulence Intensity	[-]	10.3

Unit 625 Windcube Classification at Georgsfeld

Height	Variable		m
[m]	name	unit	[% / u.v.]
129.7	Wind Shear	[-]	-3.7
	Turbulence Intensity	[-]	16.9
	Precipitation	[%]	0.009
99.7	Wind Shear	[-]	-1.1
	Turbulence Intensity	[-]	16.8
	Precipitation	[%]	0.012
79.7	Wind Shear	[-]	-0.5
	Turbulence Intensity	[-]	17.6
	Precipitation	[%]	0.013
59.7	Wind Shear	[-]	-1.2
	Turbulence Intensity	[-]	18.0
	Precipitation	[%]	0.014

Unit 625 Windcube Classification at Bremerhaven

- All Windcubes behave the same: repeatability demonstrated in "repeatability and stability of Windcube", 2016.
- Two last classifications: constant turbulence intensity sensitivity for different heights and sites.
- How to explain the sensitivity to turbulence intensity?

Agenda

- Scalar averaging : bias of RSD in comparison to cup anemometer
- Scalar averaging for Windcube : turbulence drives the bias
- Vector averaging : unbiased method

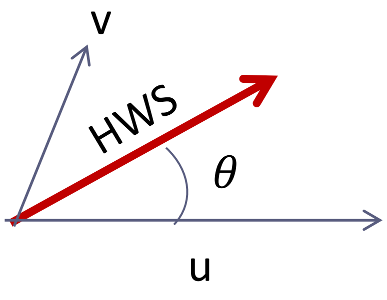
Scalar averaging : bias of RSD to cup

Definition of wind for wind energy

- For power production, the main wind characteristics used is the horizontal wind speed (in a certain range of shear/TI conditions generally). **It is a 1D value**.

- The cup anemometer measures a **1D** value : the horizontal wind speed. It does not take into account wind direction.

- A monostatic remote sensor (such as Windcube) measures the wind **2D** vector (u,v) and then calculate horizontal wind speed.



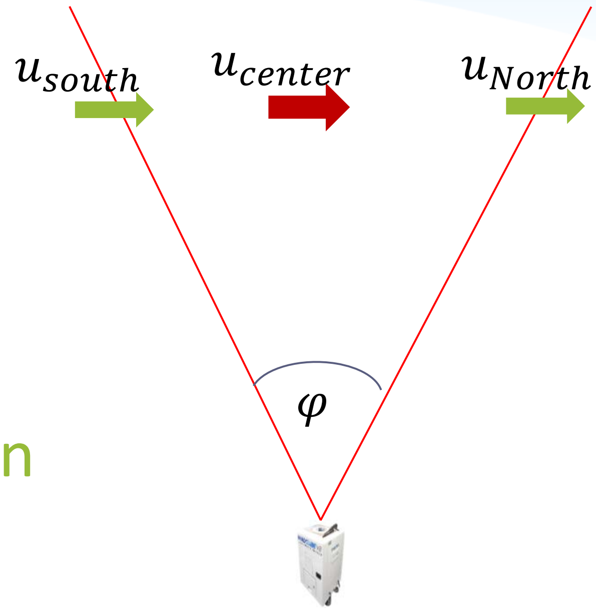
Intrinsic cup and RSD differences

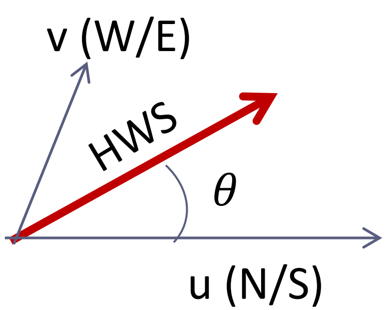
- Over 10 minutes, the cup anemometer averages all the **measured** 1D values to obtain the 10-minutes averaged horizontal wind speed,
- The RSD averages the **reconstructed** horizontal wind speed to obtain the 10-minutes averaged horizontal wind speed.

Definition of wind	Cup anemometer		RSD	
Scalar averaging	Measured 1D: HWS	10-min average: $\overline{HWS}$	Measured 2D : u v	10-min average of reconstructed $\overline{\sqrt{u^2+v^2}}$

Link between RSD and cup anemometer

- RSD DBS equations :
  - $u = \frac{u_{north}+u_{south}}{2} + \frac{w_{north}-w_{south}}{2\tan\varphi}$
  - $v = \frac{v_{west}+v_{east}}{2} + \frac{w_{west}-w_{east}}{2\tan\varphi}$
- Over one scan (4 seconds), flow is non uniform
  - $u = u_{center} + \Delta u + \frac{\Delta w}{2\tan\varphi} = u_{center} + \Delta u, w$
  - $v = v_{center} + \Delta v + \frac{\Delta w}{2\tan\varphi} = v_{center} + \Delta v, w$
- The RSD horizontal wind speed is the norm of the wind vector (u, v)





Link between RSD and cup anemometer: instantaneous

- 1D value extracted from the RSD wind vector measurement :
  - $HWS_{RSD} = \sqrt{u^2 + v^2}$
  - $HWS_{RSD} = \sqrt{(u_{center} + \Delta u, w)^2 + (v_{center} + \Delta v, w)^2}$
  - $HWS_{RSD} = \sqrt{u_{center}{}^2 + v_{center}{}^2 + (\Delta u, w)^2 + (\Delta v, w)^2 + 2u_{center}\Delta u, w + 2v_{center}\Delta v, w}$
- Cup anemometer measures the wind at the center:

Biased distribution

$$HWS_{RSD} = \sqrt{HWS_{cup}{}^2 + (\Delta u, w)^2 + (\Delta v, w)^2 + 2HWS_{cup} * (\cos(\theta) * (\Delta u, w) + \sin(\theta) * (\Delta v, w))}$$

- The average of HWS_{RSD} is higher than HWS_{cup} due to the biased term and the characteristic $\sqrt{x^2 + y^2}$

Conclusion part 1

- Wind can be defined as the average of a 1D measurement (cup) or a reconstructed 1D value from 2D measurement (RSD),

- Scalar averaging RSD differs from average of the 1D cup wind speed because of flow non uniformity over one scan period,

- The difference is statistically positively biased.

Scalar averaging for Windcube : turbulence drives the bias

Non uniformity in simple terrain : turbulence

- To simplify, we can only consider $\Delta u = \frac{u_{north}+u_{south}}{2} - u_{center}$

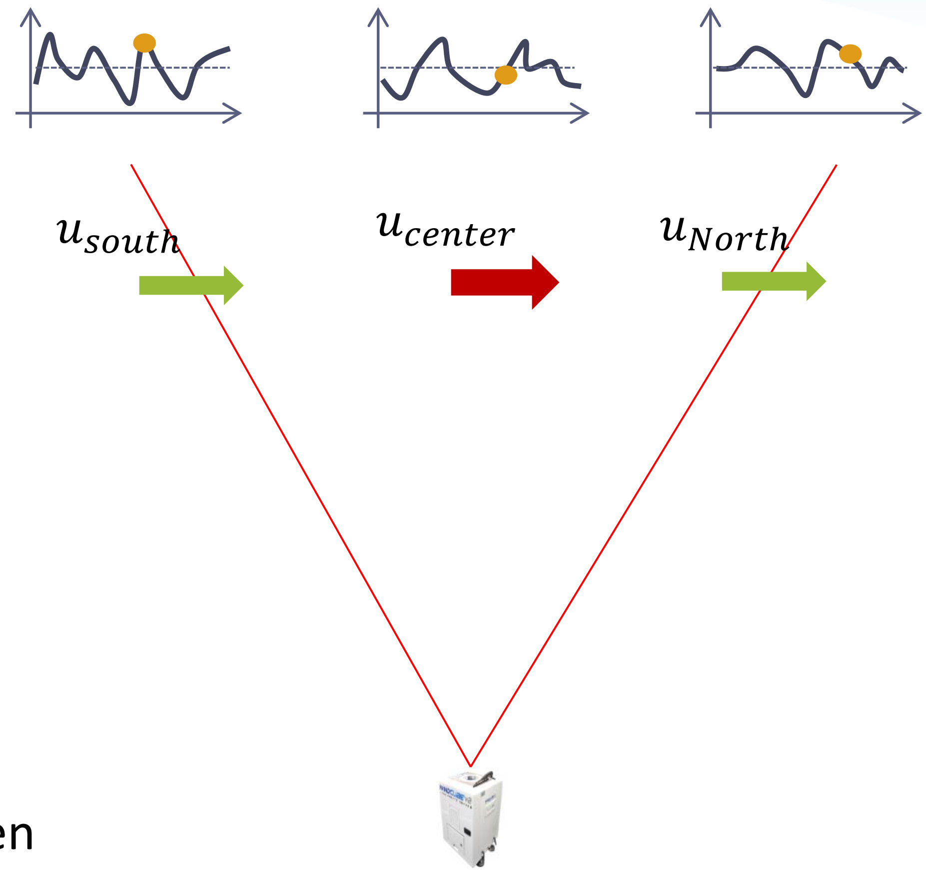
- Δu has a null mean (uniformity over 10 minutes) and a variance of (hyp: non correlated turbulence):

$$\frac{\sigma_{u_{north}}{}^2 + \sigma_{u_{south}}{}^2 + 2 \ * \sigma_{u_{center}}{}^2}{4}$$

If uniform turbulence, variance of Δu :

$$\sigma_{u_{center}}{}^2$$

- If non fully uncorrelated turbulence then variance is expected to be lower.



u wind speeds are not fully correlated across the volume of scan

Example of deviations

Deviation model:

$$HWS_{RSD} = \sqrt{{HWS_{cup}}^2 + (\Delta u, w)^2 + (\Delta v, w)^2 + 2HWS_{cup} * (\cos(\theta) * (\Delta u, w) + \sin(\theta) * (\Delta v, w))}$$

Input for this example:

$u = HWS * \cos(\theta)$

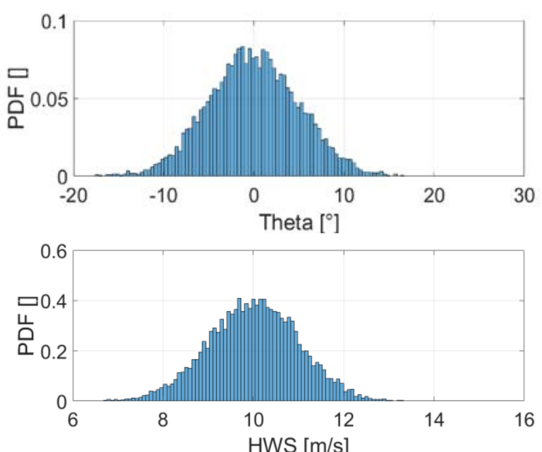
$v = HWS * \sin(\theta)$

Direction variance =5°

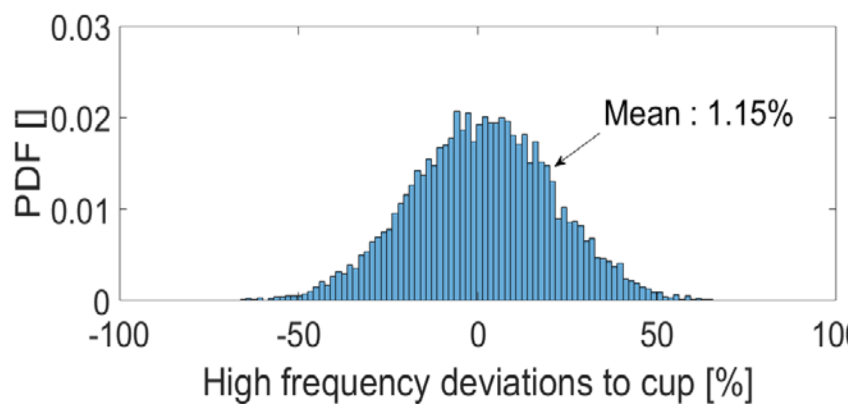
w=0

TI=10%

Uncorrelated turbulence



Devation model

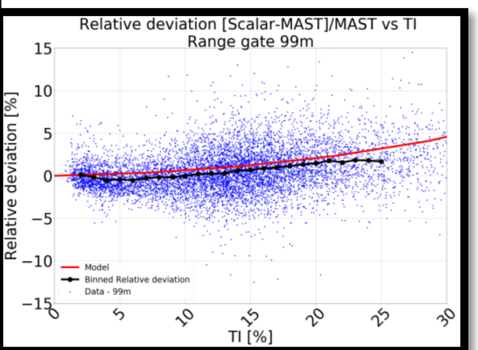


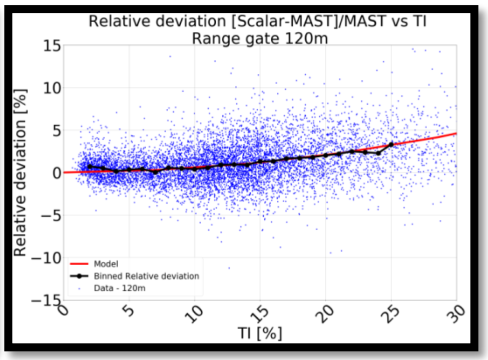
RSD Monte Carlo simulation

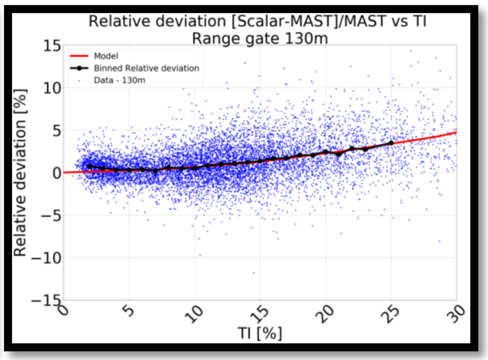
Inputs
- Sigma U
- Sigma V

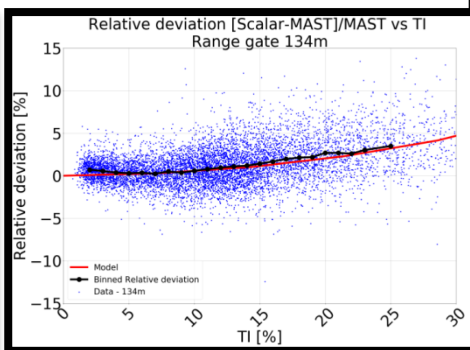
Monte-Carlo simulation
1000 realisations
- Generation of U and V @ 1hz
- Calcul of Scalar Vh @ 10min equivalent (composed of 600 U and V)
- Calcul of relative deviation@ 10min

Results
- Relative Deviation per TI









- Simulated deviation in ideal turbulence wind field (w=0, fully uncorrelated turbulence)
- **It agrees well with cup deviations observed on site**
- Scatter come from the correlation of turbulence and W (stability)

Conclusion part 2

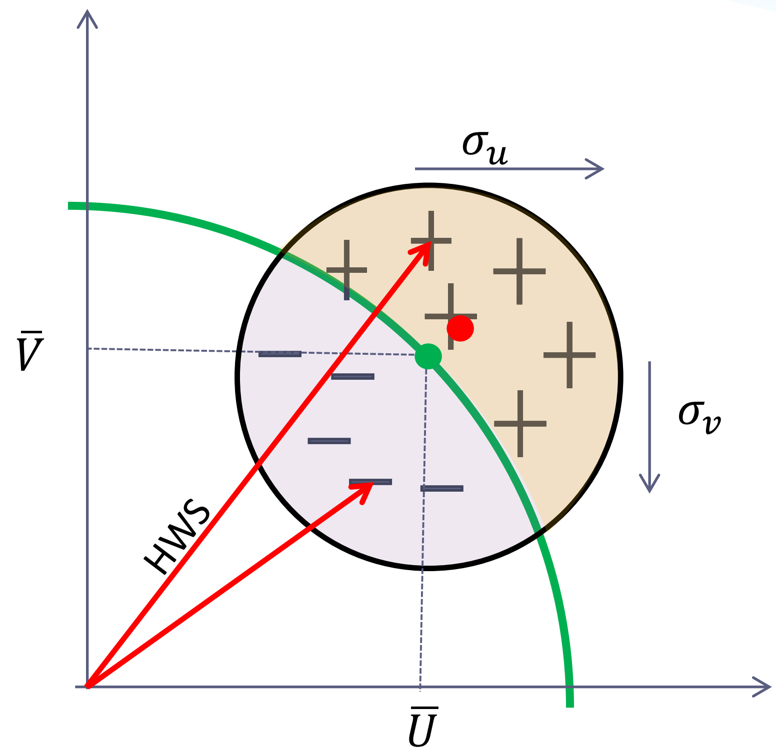
- The difference between average 1D cup anemometer wind speed and scalar averaged RSD wind vector is driven by turbulence of wind speed and turbulence of wind direction,

- The bias is, among others things, composed of spatial correlation of turbulence of horizontal wind speed or vertical wind speed thus difficult to calculate.

Vector averaging : unbiased method for horizontal wind speed calculation

10-min scalar average overestimation

- The wind can be considered as:
  - Vector : the 2D mean $|(\bar{U},\bar{V})|$
  - OR Scalar : the 1D mean $\overline{HWS}$
- In case of turbulence: $\overline{HWS}$ is higher than $|(\bar{U},\bar{V})|$
- Known results: Averaging the vector is not sensitive to variance of the U and V unlike scalar averaging.



Points are couple of U and V measured over 10 minutes, red arrow are example of vector with the HWS scalar value and green line is a constant HWS value curve

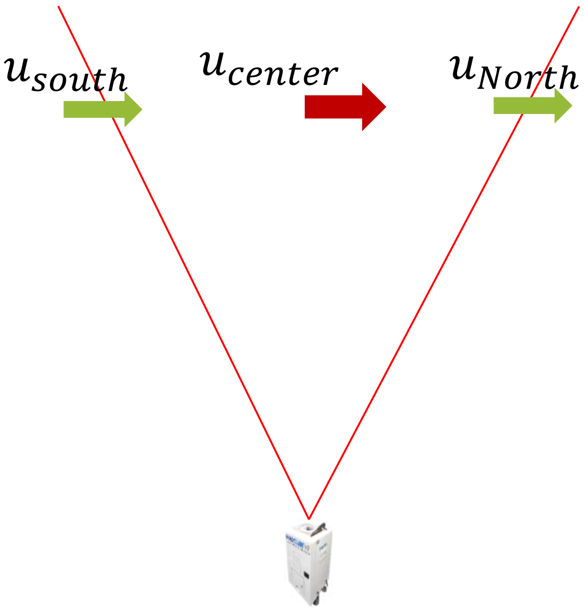
Intrinsic cup and RSD differences

- The difference between scalar and vector averaging for cup is not the same as the difference between scalar and vector averaging for RSD

Definition of wind	Cup anemometer		RSD	
Scalar averaging	Measured 1D: HWS	10-min average: $\overline{HWS}$	Measured 2D : u v	10-min average of reconstructed $\overline{\sqrt{u^2+v^2}}$
Vector averaging	Measured 2D: HWS $\theta\ (from\ wind\ vane)$	10-min average of reconstructed : $\sqrt{\overline{HWS*\cos(\theta)}^2+\overline{HWS*\sin(\theta)}^2}$	Measured 2D : u v	10-min average of reconstructed $\sqrt{\bar{u}^2+\bar{v}^2}$

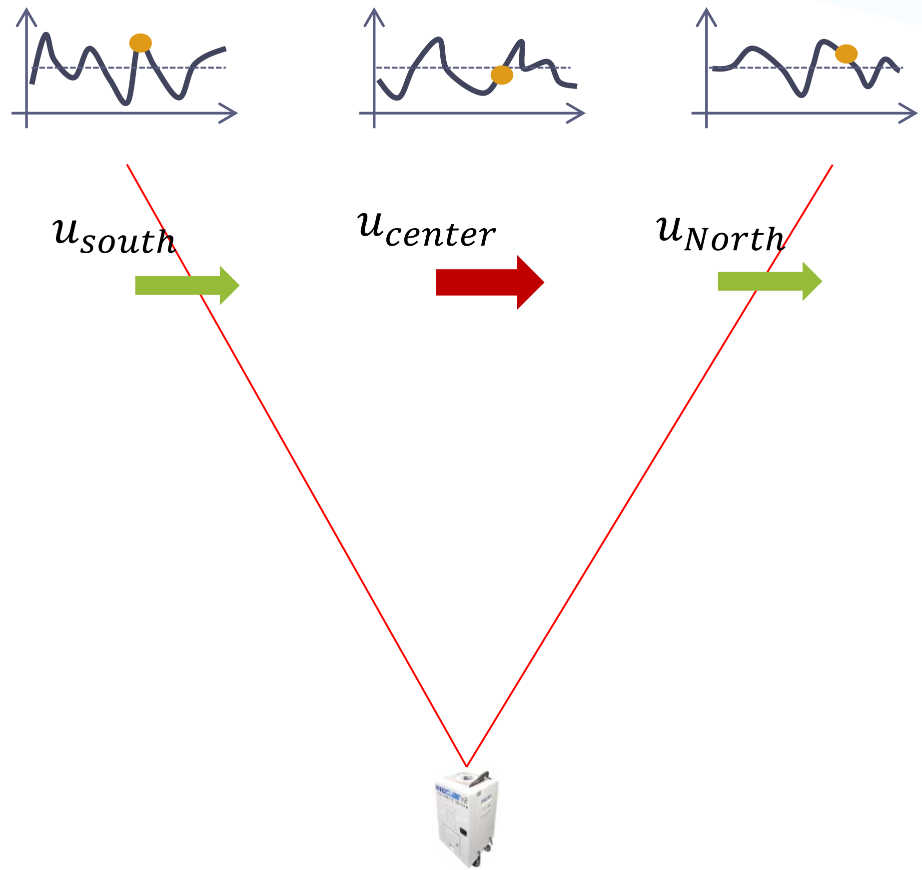
Link between RSD and cup anemometer instantaneous

- Lidar equations :
  - $u = \frac{u_{north}+u_{south}}{2} + \frac{w_{north}-w_{south}}{2\tan\theta}$
  - $v = \frac{v_{west}+v_{east}}{2} + \frac{w_{west}-w_{east}}{2\tan\theta}$
- Over one scan (4 seconds), flow is non uniform
  - $u = u_{center} + \Delta u + \frac{\Delta w}{2\tan\theta} = u_{center} + \Delta u, w$
  - $v = v_{center} + \Delta v + \frac{\Delta w}{2\tan\theta} = v_{center} + \Delta v, w$
- The vector wind speed is the average of the wind vector (u, v).



Non uniformity in simple terrain : turbulence

- To simplify, we can only consider $\Delta u = \frac{u_{north}+u_{south}}{2} - u_{center}$
- Δu has a null mean (uniformity over 10 minutes) : $\overline{\Delta u} = 0$
- $\overline{u_{center} + \Delta u} = \overline{u_{center}}$
- The turbulence has no impact on the mean value

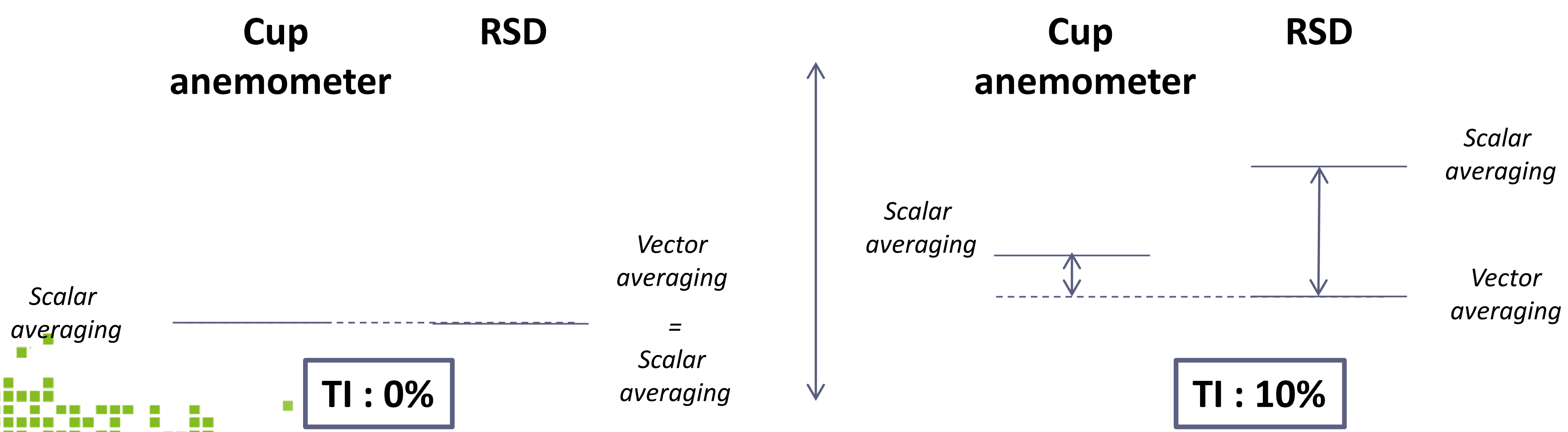


u wind speeds are not fully correlated across the volume of scan

Expected accuracy of vector average

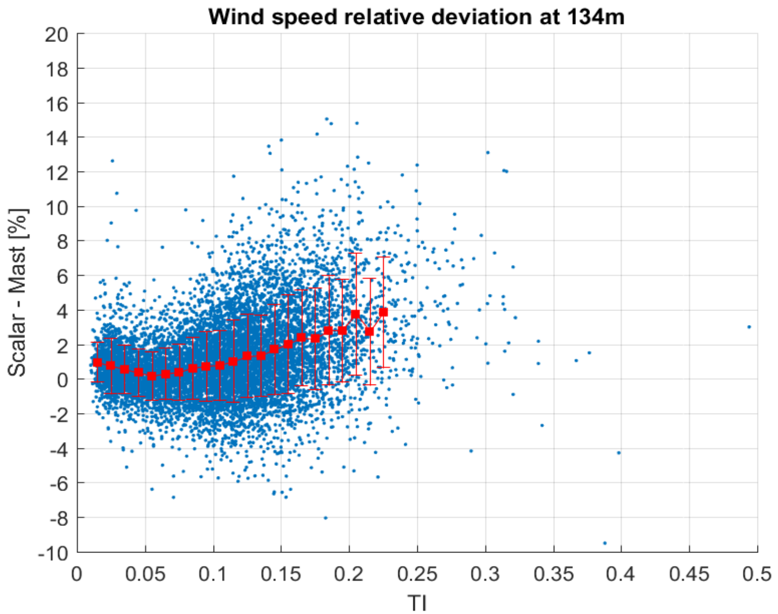
- Since cup anemometer scalar value is little sensitive to TI, RSD vector averaging is closer to cup anemometer scalar averaging

$$HWS_{RSD_{vector}} = \sqrt{\overline{u_{center}}^2 + \overline{v_{center}}^2}$$

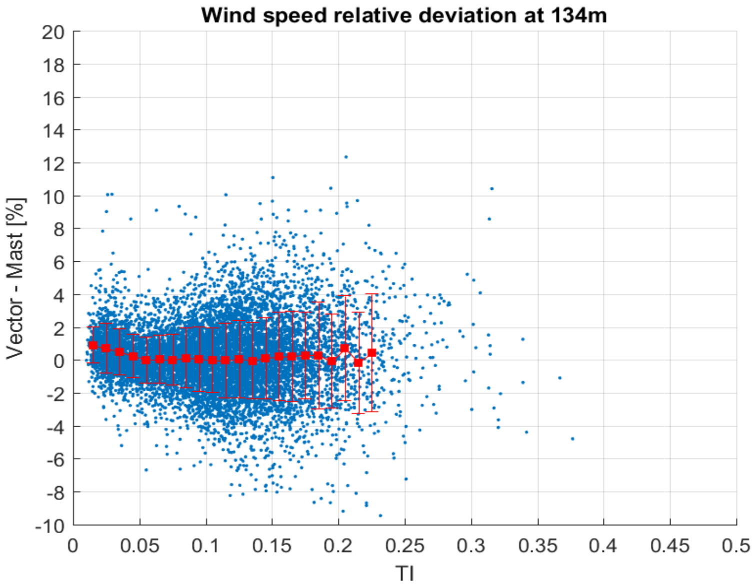


Vector averaging : on site observations

- Comparison of scalar and vector averaging of RSD to scalar average of cup confirms low sensitivity



Scalar



Vector

Conclusion

- Low uncertainty = Good LCOE
- Sensitivity of Windcube are understood : scalar averaging sensitive to turbulence
- Vector averaging: no TI sensitivity.

Questions?